

## SLOPE PROFILOMETRY OF GRAZING INCIDENCE OPTICS\*

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### **Abstract**

Profiling instruments are well-suited to the measurement of grazing incidence optics, such as those found in synchrotron radiation beam lines. Slope measuring profilers, based upon the principle of the pencil beam interferometer, have proven to be especially useful in measuring the figure and slope errors on cylindrical aspheres. The Long Trace Profiler, in various configurations, is the most widely used of this class of profiler. Current performance provides slope measurement accuracy at the microradian level and height measurements accurate to 25 nm over 1 meter trace lengths.

### **1. Introduction**

The tight tolerances required in the fabrication of precision machined optics often exceed the measurement capabilities of mechanical probes. The accuracy level required is available through optical interferometry methods. But conventional interferometers are not suited to measure aspheric parts that depart significantly from a plane or spherical shape. This is especially true for segments of cylinders found in grazing incidence synchrotron light source beam line optics. A convenient and versatile method for measuring the shape of these unconventional surfaces is by profilometry.

There are two basic types of profiling instrument: height or displacement measuring devices, and slope or angle measuring devices. Height-measuring instruments measure the distance between the test surface and a reference surface, while slope-measuring instruments measure either the differential phase shift between two closely-spaced probe beams or the angle of a reflected laser beam directly. Height-measuring profilers are extremely sensitive to vibrations and other

environmental instabilities that cause changes in the optical paths between the test and measurement arms. Slope profilers, on the other hand, are essentially differential measurement devices. They are almost completely insensitive to vibrations that produce changes in the distance to the test object. They also provide slope error information directly, which is the item of primary interest to users of grazing incidence optics.

## **2. Slope profilers**

Slope profiling instruments traditionally have operated on the principle of the optical lever, where an angular deviation of a probe beam is magnified and recorded with a high gain amplifier, or on the principle of the autocollimator. R.V. Jones chronicles the development of sensitive optical lever instruments capable of measuring nanoradian angular deflections[4]. Increased interest in telescopes for x-ray astronomy in the 1960's and 70's led to the development of an optical lever device to measure slope errors on x-ray optics several centimeters in length[7,15]. The Random Devices Slope Scanner used a clever air bearing slide mechanism to move the probe beam along a circular arc that matched the curvature of the part under test[2]. This motion always kept the surface near the focus of the laser beam spot. The deflection of the reflected beam was measured with a resolution of a few tenths of an arc second by the differential signal from a pair of photodiodes. As DeCew notes, the limitation in the measurement accuracy was not in the optical system, but was in the tolerances of the mechanical translation system. With the advent of new, dedicated synchrotron radiation sources in the 1980's, it was apparent that there was a need for an accurate and versatile metrology instrument that could quickly measure the shape of long cylindrical aspheres.

## **3. Long Trace Profiler Development**

The Long Trace Profiler (LTP) is currently the most widely used instrument for measuring the surface figure of synchrotron beam line optics[16,17,19]. Its design is based upon the principle of the pencil beam interferometer, originally developed by von Bieren in 1982[21,22]. The optical head design is quite simple, with no internal moving parts during the measurement to insure long-term stability and maintain high accuracy. An advantage of the pencil beam interferometer over microscope-based

systems is the effectively infinite depth of field of the probe beam, which relaxes the tolerances on test piece alignment and allows for rapid setup and testing.

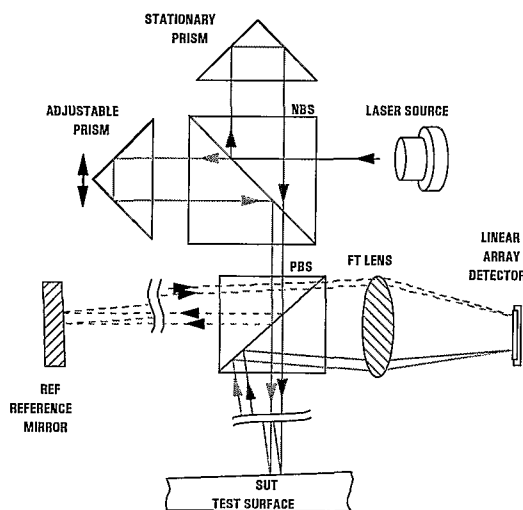


Fig. 1 – Sketch of basic LTP II optical system.

the two components of the probe beam when the Porro prism is translated. After exiting the NBS, the probe beam passes through a half-wave plate, HWP, which is adjusted to balance the intensities after passing through the polarizing beamsplitter, PBS. The PBS passes the light that is p-polarized onto the test surface, SUT, while reflecting the s-polarized fraction to the reference mirror, REF. Each polarized beam passes through a quarter-wave plate on the outbound and inbound leg, resulting in a net rotation of each polarization direction by  $90^\circ$ . Thus, on the return through the PBS, each beam is directed into the Fourier transform lens. A folding mirror system (not shown) directs both beams onto a linear array detector placed at the back focus of the lens.

During the development of the LTP II instrument, it became apparent that the pencil beam profiling technique was well-suited for a number of other measurement problems. A vertical-scan system (VSLTP), shown in Fig. 2, was built for NASA Marshall Space Flight Center to measure the inside of complete x-ray telescope cylinders[5,6]. Qian developed an *in situ* version that was used to measure the distortion of a SR mirror under actual operating conditions while installed in a beam

line at ELETTRA in Trieste, Italy[9,12]. An improved version of this instrument was developed for use at the Advanced Photon Source, where significant distortion was measured on a side-cooled silicon mirror in an undulator beam line[20]. A new version of the optical head, developed under a CRADA collaboration with Ocean Optics, Inc. (OOD), has been installed on the ELID grinding machine at RIKEN in Tokyo. This system is interfaced with the existing machine motion control system and includes a beam-steering mirror to enable measurement of the full 3D surface profile of cylinder mirrors.

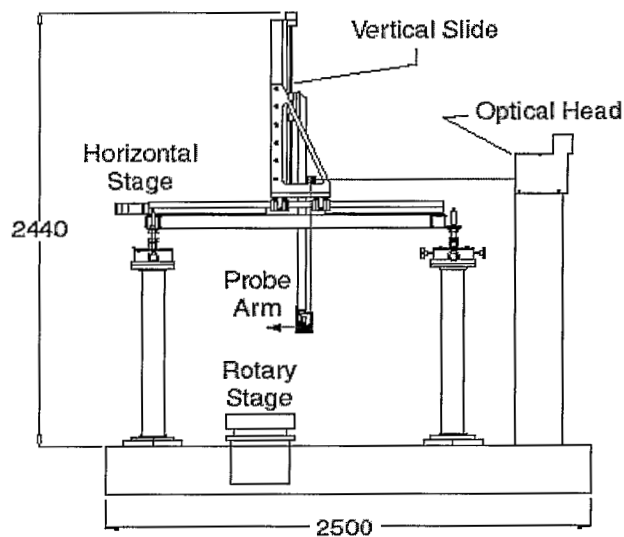


Fig. 2 – Schematic of Vertical Scan LTP configured for 3D measurement of complete Wolter telescope x-ray mirrors and mandrels. Penta prisms direct the beam onto the test object that mounts on the rotary stage. Dimensions in millimeters

Other groups are also pursuing research into improving the performance of the pencil beam interferometer system. Workers at the Changchun Institute of Optics have developed an instrument to measure the complete 3D topography of surfaces with azimuthal symmetry[23]. The test object is mounted on a precision rotary stage, and a series of meridional measurements is made at regular azimuthal angle spacings. A large reference flat is mounted under the test object to provide information about the tilt angle of the surface at a particular azimuthal angle. Chatterjee and Kumar [1] have devised a beam splitting arrangement that produces the separated probe pair by use of a pair of plane mirrors in place of the Porro prisms. The plane mirrors are arranged much like the reflecting surfaces of a penta prism.

The LTP can be operated in two basic configurations. The standard configuration places the optical head on a linear translation stage and moves the entire optical head over the surface that is being measured (moving head). The

alternative configuration places the stationary optical head off to the side with the test beam directed horizontally to a penta prism that directs the probe beam down to the test surface (fixed head). The penta prism is scanned over the surface. This is the original measurement method proposed by von Bieren[21,22]. Each configuration has advantages and disadvantages. The moving optical head requires a high quality translation stage to minimize pitch angle errors during the scan. The reference beam must be used to correct for residual pitch errors during the scan caused by the sag of the translation stage and jitter in the motion. The moving penta prism, however, always redirects the incident beam by exactly  $90^\circ$ , independent of the errors in the translation stage. Use of a reference beam is optional in this case[8-13]. Use of the penta prism also greatly relaxes the tolerances on the translation mechanism. The penta prism LTP can be configured to provide measurements in difficult environments, such as inside complete x-ray telescope cylinders[3,5,6,13,18] and *in situ* at SR beam lines during actual operations.

One of the major error sources in the LTP II arises from instability in the optical path difference between the components of the probe beam as they pass through the NBS and the Porro prisms. The three elements are mounted on separate stages and are subject to extremely small changes in position and temperature due to environmental effects. These changes produce nanometer-level changes in the optical path between the beams, which results in fringe motion on the order of several microradians during a typical scan. Qian[14] has developed a monolithic beam splitter prism that eliminates the drift between separated components. Although the separation distance between the probe beams is now fixed, the fringe drift is much less than 0.5

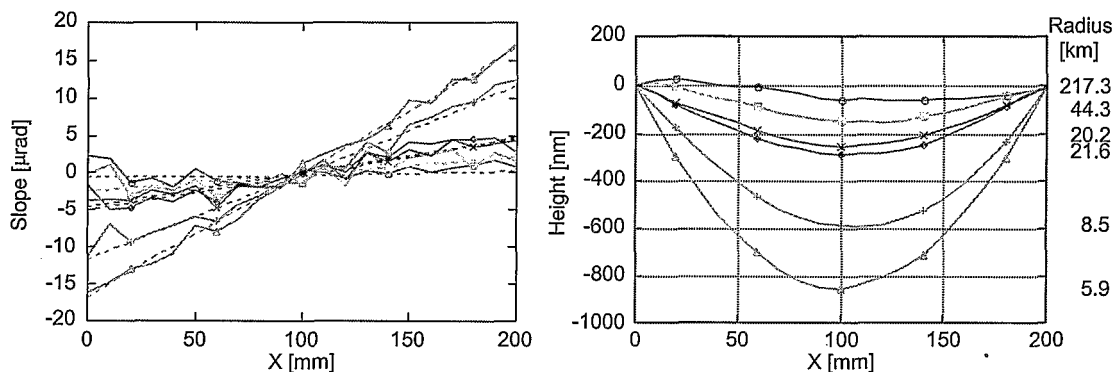


Fig. 3 – LTP measurements on a bent cylinder mirror. Slope profile for relaxed condition is subtracted from all subsequent measurements in frame on left. Height profiles integrated from slopes shown in frame on right. Radius values for various bend conditions are as indicated. Surface sag of 25 nm over 200 mm is clearly seen.

microradian over a several hour period. Zhao, et al.[24] have developed an ingenious method for producing a probe beam that is also absolutely stable against environmental effects. They use a phase step etched into a thin plate to produce a phase shift of  $\lambda/2$  in one half of the laser beam.

Examples of measurements made with the LTP at BNL are shown in Fig. 3. These measurements were made on a silicon cylinder mirror mounted face-down in a bending apparatus. The probe beam from the LTP is turned by  $180^\circ$  and is directed up to the surface by a pair of penta prisms. The bender actuator is driven to various settings and the slope profile is measured relative to the initial unbent profile. A slope change of  $2 \mu\text{rad}$  is clearly visible over the 200 mm trace length. The height profile integrated from the slope has a radius of curvature of over 200 km with a sag of 25 nm.

The current LTP configuration in the Optical Metrology Lab at BNL is shown in Fig. 4. The optical head is structured as an inverted "T", with the beamsplitting optics in the lower part and the detector and folding mirrors along the stem. The system is built around the use of Microbench components and is easily configured to perform various functions. It is used both for production metrology work and as a test-bed system for evaluating new ideas. A folding mirror system, comprised of 2 flat mirrors along the stem of the "T" shorten the distance between the optical head and the detector. The system is shown configured for a 1250 mm focal length lens, the longest possible for this system. The travel length on the linear air bearing travel is nearly 1 meter. Current work with this system involves investigating sources of systematic error that affect the measurement accuracy at the  $1 \mu\text{rad}$  level and below.

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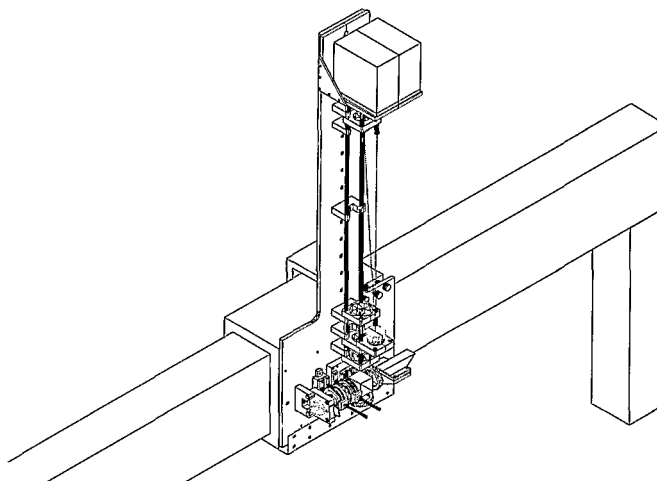


Fig. 4 – Current BNL LTP configuration. "Open architecture" allows for rapid prototyping and testing of internal components.

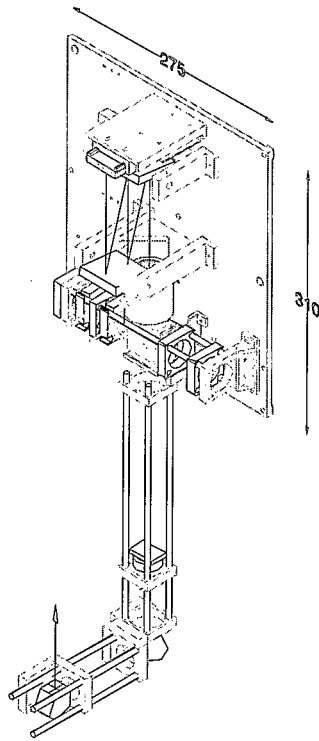


Fig. 5 – LTP IV optical head with compact folded lens-to-detector beam path. The dual penta prism attachment is used to measure mirrors in the face-down configuration.

of the LTP optical head is shown in Fig. 5. The LTP IV optical head, developed in collaboration with Ocean Optics, has a surface slope measurement range of 12 mrad with a lens focal length of 584 mm. It utilizes a standard USB-interface detector array from OOI. The optical path to the detector is folded by 4 reflections off of two mirrors to decrease the size of the package footprint. This is a moving head system, where the optical head is mounted onto the moving linear stage. Also shown in the figure is the dual penta prism attachment that is used to direct the probe beam in the upward direction to measure mirrors in the face-down configuration. Current research efforts are directed toward developing a more compact optical head with stability and accuracy at the  $0.1 \mu\text{rad}$  level.

#### 4. Acknowledgment

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#### 5. References

1. Chatterjee, S. and Kumar, Y. P., 2002, *Applied Optics* 41, 5857-5859



2. DeCew, A. E., Jr. and Wagner, R. W., 1986, Proc. SPIE 645, 127-132.
3. Gubarev, M., Kester, T., and Takacs, P. Z., 2001, Proc. SPIE 4451, 333-339.
4. Jones, R. V., 1988, *Instruments and Experiences: Papers on Measurement and Instrument Design*, (John Wiley & Sons, Ltd.).
5. Li, H., Li, X., Grindel, M. W., and Takacs, P. Z., 1996, Opt. Eng. 35, 330-338
6. Li, H., Takacs, P. Z., and Oversluizen, T., 1997, Proc. SPIE 3152, 180-187.
7. Price, R. H., Low Energy X-ray Diagnostics 75, (AIP), 189-199.
8. Qian, S., Jark, W., Sostero, G., et al., 1996, Synchrotron Radiation News 9, 42-44
9. Qian, S., Jark, W., Sostero, G., Gambitta, A., Mazzolini, F., and Savoia, A., 1996, Proc. SPIE 2856, 172-182.
10. Qian, S., Jark, W., and Takacs, P. Z., 1995, RSI 66, 2562-2569
11. Qian, S., Jark, W., Takacs, P. Z., Randall, K. J., Xu, Z., and Yun, W., 1996, RSI 67, 3369.
12. Qian, S., Jark, W., Takacs, P. Z., Randall, K. J., and Yun, W., 1995, Opt. Eng. 34, 396-402
13. Qian, S., Li, H., and Takacs, P. Z., 1996, Proc. SPIE 2805, 108-114.
14. Qian, S. and Takacs, P. Z., 2003, Opt. Eng. (in press)
15. Silk, J. K., 1980, Annals of the New York Academy of Sciences 342, 116-129
16. Takacs, P. Z., Feng, S. K., Church, E. L., Qian, S., and Liu, W.-M., 1989, Proc. SPIE 966, 354-364.
17. Takacs, P. Z., Furenlid, K., DeBiasse, R., and Church, E. L., 1989, Proc. SPIE 1164, 203-211.
18. Takacs, P. Z., Li, H., Li, X., and Grindel, M. W., 1996, RSI 67, 3368-3369.
19. Takacs, P. Z., Qian, S., and Colbert, J., 1987, Proc. SPIE 749, 59-64.
20. Takacs, P. Z., Qian, S. N., Randall, K. J., Yun, W. B., and Li, H., 1998, Proc. SPIE 3447, 117-124.
21. von Bieren, K., 1982, Proc. SPIE 343, 101-108.
22. von Bieren, K., 1983, Appl. Opt. 22, 2109-2114
23. Yu, J., Xu, J., Zhang, X., and Sun, X., 1995, Proc. SPIE 2536, 192-199.
24. Zhao, Y., Li, Z., Li, D., Tiquiao, X., and Shaojian, X., 2001, Opt. Com. 200, 23-26